# X-ray Magnetic Linear Loops: A Method for the Measurement of Anisotropy and Rotational Hysteresis

A method has been developed that permits the measurement of magnetocrystalline anisotropy using x-ray magnetic linear dichroism. Measurements on thin films of iron have validated the method.

Many applications of magnetic materials are to be found in diverse areas. For example, a typical automobile will contain a few dozen sensors, many using magnetic materials. Another area of importance is the data-storage sector. Due to the ever-increasing demand for greater storage capacities, a large industry and subsequently large research effort have developed. This effort is aimed at improving storage materials through a better understanding of their underlying physical properties. The ultimate goal is to fully describe how a material behaves magnetically. Among many relevant magnetic properties, one is of particular importance and will be the focus of this article: the magnetocrystalline anisotropy energy. A number of experimental methods can be used to measure the anisotropy. This article describes the development of x-ray magnetic linear loops (XMLL), a new method using the intense polarized x-rays available at synchrotrons. How XMLL works and its advantages are discussed below.

A magnetic material consists of many individual magnetic moments that can be oriented in any direction. If a material contains a single domain and one were to take a macroscopic average of the direction of the moments, one can define a magnetization direction for the material. If an external magnetic field, ***H***, is applied to the material, the magnetization, ***M***, will rotate so as to minimize the total energy. Where these energy minima are located is determined by the properties of the material (e.g., crystal structure). We will consider two types of materials here. The first is polycrystalline materials in which the atoms are arranged in a disordered fashion inside the material. In this case, if an external field is applied, the magnetization will rotate to orient itself along the field direction. The second type of material is one in which the atoms are oriented in an ordered crystal structure. For example, consider a simple cubic system where the atoms are located on the corners of a cube. In this case, energy minima are now located along the cube edges. Thus if a field is applied, ***M*** will rotate so as to balance being along ***H*** and along the energy minimum. The term in the energy that gives rise to the energy minimum is called the magnetocrystalline anisotropy energy [1].

Now that we know what the anisotropy energy is, how is it measured? A number of techniques can be employed. Most of these require many individual measurements to determine the anisotropy of a material. Furthermore, they are bulk measurements, meaning they measure an average of all the magnetic elements in a material. Given that many technologically important materials consist of multiple elements, this is a disadvantage when trying to understand the underlying physics. Using the intense x-rays generated at a synchrotron and a technique called x-ray magnetic dichroism (XMD) [2], it is possible to measure each element separately. While the details of the dichroism effect are beyond the scope of this article, some basics are necessary to understand XMLL. When x-rays are incident on a material, a number of processes take place. One of these is that an x-ray photon can be absorbed by an electron, ejecting the electron from the atom. The number of electrons ejected will vary with the x-ray energy, reaching the maximum when the x-ray energy corresponds to the "binding energy" of an element in the sample. The number of electrons will also vary with the magnetic state of the sample. By measuring this change (the dichroism), one gets information about the magnetic moment of the material. The XMLL technique uses the dichroism effect to obtain anisotropy information.

The experimental setup is shown in Fig. 1. Linearly polarized x-rays, tuned to the binding energy of an element, are incident on the sample. An external magnetic field is applied and is rotated through

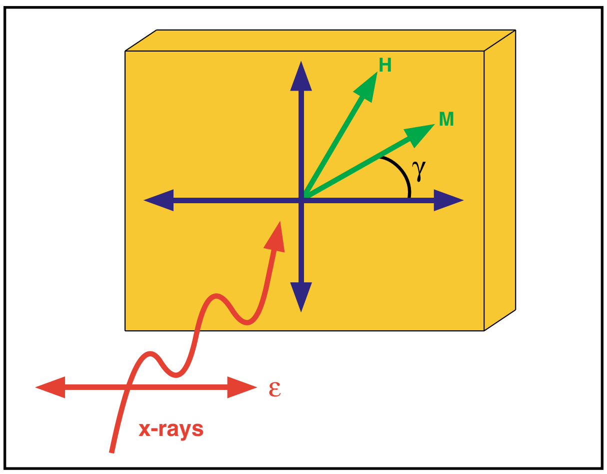


*FIG. 1. Schematic diagram of the setup for the XMLL experiment.*

360° in the plane of the sample. As the angle of ***H*** changes, ***M*** will rotate to minimize the energy. With a weak anisotropy, ***M*** will move relative to the x-ray polarization, $\hat{\varepsilon}$, according to:

$$\text{XMLL} = \langle (\text{M} \bullet \hat{\varepsilon})^2 \rangle = \text{M}^2\cos 2\gamma$$

If there is a strong anisotropy, then ***M*** is prevented from following ***H***. In this case the measured XMLL will vary from this ideal relationship.

As a proof-of-concept experiment, we looked at two samples. Both of them are Fe thin films; one has a polycrystalline crystal structure (weak anisotropy), while the second has a cubic crystal structure (strong anisotropy). The XMLL data from these

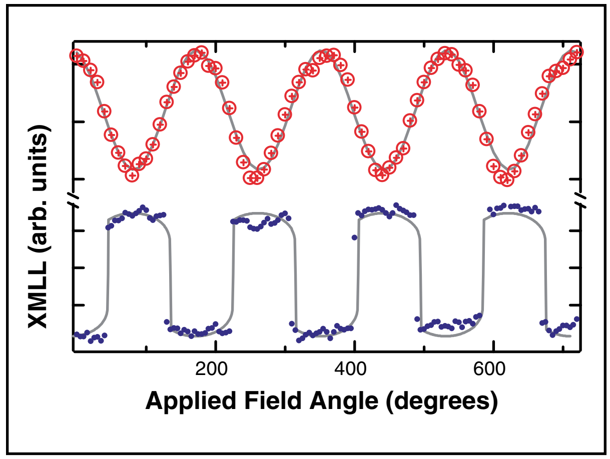


*FIG. 2. XMLL vs applied field angle for (top) a polycrystalline Fe/weak anisotropy sample, and (bottom) a bcc single-crystal Fe/strong anisotropy sample.*

samples are shown in Fig. 2. The red-circled crosses are the data from the sample with weak anisotropy. The gray line overlaying this data is a plot of cos2γ. Clearly, there is good agreement between the two, implying that indeed ***M*** rotates with ***H*** in this sample and that, in the case of weak anisotropy, our relation holds true. As we suspected, the sample with strong anisotropy shows deviation from this. The data from the second sample are shown as blue dots at the bottom of Fig. 2. Note that the frequency of the curve is the same as for the polycrystalline sample. Thus, ***M*** mostly rotates with ***H*** according to our relation. However, there are now sharp steps every 90°, making the XMLL into a square wave. Why is this? Remember that, for a cubic sample, the anisotropy causes energy minima along the cube edge (located along the blue axes shown in Fig. 1). Thus, there must be a peak in the energy in between the minima. This peak serves as a barrier to the rotation of ***M*** with ***H***. As ***H*** is rotated over the peak, ***M*** will stay in the first energy minima until there is enough energy and then will jump the barrier to the next minimum. The gray line overlaying this plot is the result of a numerical simulation that confirms this interpretation.

What is the practical importance of this technique? The experiment that we have discussed here shows the feasibility of measuring XMLL. Materials that are of technological interest are more complex than the ones measured here. Typically, they consist of multiple interacting elements and exhibit complex dynamics. Thus, to gain a firm understanding of these complex materials it is advantageous to look at each element separately. Given that it is an element-specific technique, XMLL makes it possible to identify each element's contribution to the overall anisotropy. This will help to tailor anisotropy properties for novel magnetic materials.

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